ELECTROMAGNETIC DETECTION OF AXIONS

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Abstract

Photon-to-axion conversions in the static electromagnetic fields are reconsidered in detail by using the Feynman diagram techniques. The differential cross sections are presented for the conversions in the presence of the electric field of the flat condenser as well as in the magnetic field of the solenoid. Based on our results a laboratory experiment for the production and the detection of the axions is described. This experiment will exploit the axion decay constant as well as the axion mass.

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In the 1970's, it was shown that the strong CP problem can be solved [1] by the introduction of a light pseudoscalar particle, called the axion [2]. However, no positive indication of its existence has been obtained so far. At present, the parameters of axions are constrained by laboratory searches [3] and by astrophysical and cosmological considerations [4].

A particle, if it has a two-photon vertex, may be created by a photon entering an external electromagnetic (EM) field. An axion is one of such particles. Conversion of the axions into EM power in a resonant cavity was firstly suggested by Sikivie [5]. He suggested that this method can be used to detect the hypothetical galactic axion flux that would exist if axions were the dark matter of the Universe. Various terrestrial experiments to detect invisible axions by making use of their coupling to photons have been proposed [6, 7, 8], and the first result of such experiments appeared recently [9].

Recently, a photon regeneration experiment, using RF photons, was described [10]. That experiment consists of two cavities which are placed a small distance apart. A more or less homogeneous magnetic field exists in both cavities. The first, or emitting is excited by incoming RF radiation. Depending on the axion-photon coupling constant, a certain amount of RF energy will be deposited in the second, or receiving cavity. In Ref. [10] the author considered the problem by using the classical method. By applying the Feynman diagram techniques we have considered the conversion of the photons into gravitons in the static [11] and periodic [12] EM fields. In this paper we also apply this method to reconsider the EM conversion of the axions in both the electric and magnetic fields.

The axion mass and its couplings to ordinary particles are all inversely proportional to the magnitude v of the vacuum expectation value that spontaneously breaks the $U_{PQ}(1)$ quasisymmetry which was postulated by Peccei and Quinn and of which the axion is the pseudo-Nambu-Goldstone boson. For the axion-photon system a suitable Lagrangian density is given by [4, 5]:

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + g_\gamma \frac{\alpha}{4\pi}\frac{\phi_a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\partial_\mu\phi_a\partial^\mu\phi_a - \frac{1}{2}m_a^2\phi_a^2[1+0(\phi_a^2/v^2)] \tag{1}$$

where ϕ_a is the axion field, m_a its mass, $\tilde{F}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$, and f_a is the axion decay constant and is defined in terms of the axion mass m_a by [5, 9]: $f_a = f_\pi m_\pi \sqrt{m_u m_d}[m_a(m_u + m_d)]^{-1}$. The coupling constant in (1) is model dependent. Interaction of the axions to the photons arises from the triangle loop diagram, in which two vertices are interactions of the photon to electrically charged fermion and an another vertex is coupling of the axion with fermion. This coupling is model dependent and is given:

$$g_\gamma = \frac{1}{2}\left(\frac{N_e}{N} - \frac{5}{3} - \frac{m_d - m_u}{m_d + m_u}\right),$$

where $N = \mathrm{Tr}(Q_{PQ}Q_{color}^2)$ and $N_e = \mathrm{Tr}(Q_{PQ}Q_{em}^2)$. Tr represents the sum over all left-handed Weyl fermions. Q_{PQ}, Q_{em}, and Q_{color} are respectively the Peccei-Quinn

charge, the electric charge, and one of the generators of $SU(3)_c$. In this paper we are considering very light, and very weak interacting invisible axions [13], however our calculation is also valid for the heavy axions case. In this model - the Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) model, one has $N_e = \frac{8}{3}N$ hence the coupling constant $g_\gamma(DFSZ) \simeq 0.36$. In other model as given by the Kim-Shifman-Vainshtein-Zakharov [14], where the axions do not couple to light quarks and leptons (hadronic axion), one has $N_e = 0$ and hence $g_\gamma(KSVZ) \simeq -0.97$.

Consider the conversion of the photon γ with momentum q into the axion a with momentum p in an external electromagnetic field.

For the abovementioned process, the relevant coupling is the second term in (1). Using the Feynman rules we get the following expression for the matrix element

$$\langle p|M|q\rangle = -\frac{g_{a\gamma}}{2(2\pi)^2\sqrt{q_0 p_0}}\varepsilon_\mu(\vec{q},\sigma)\varepsilon^{\mu\nu\alpha\beta}q_\nu\int_V e^{i\vec{k}\vec{r}}F^{class}_{\alpha\beta}d\vec{r} \tag{2}$$

where $\vec{k} \equiv \vec{q} - \vec{p}$ the momentum transfer to the EM field, $g_{a\gamma} \equiv g_\gamma\frac{\alpha}{\pi f_a} = g_\gamma\alpha m_a(m_u + m_d)(\pi f_\pi m_\pi\sqrt{m_u m_d})^{-1}$ and $\varepsilon^\mu(\vec{q},\sigma)$ represents the polarization vector of the photon.

Expression (2) is valid for an arbitrary external EM field. In the following we shall use it for two cases, namely conversion in the electric field of a flat condenser and in the static magnetic field of the solenoid. Here we use the following notations: $q \equiv |\vec{q}|, p \equiv |\vec{p}| = (q_o^2 - m_a^2)^{1/2}$ and θ is the angle between $\vec{p}$ and $\vec{q}$.

Conversion in the presence of an electric field.– Now we take the EM field as a homogeneous electric field of a flat condenser of size $a\times b\times c$. We shall use the coordinate system with the x axis parallel to the direction of the field, i.e., $F^{10} = -F^{01} = E$. Then the matrix element is given by

$$\langle p|M^e|q\rangle = \frac{g_{a\gamma}}{(2\pi)^2\sqrt{q_0 p_0}}\varepsilon_\mu(\vec{q},\sigma)\varepsilon^{\mu\nu 01}q_\nu F_e(\vec{k}), \tag{3}$$

where a form factor for the electric region [5, 6]

$$F_e(\vec{k}) = \int_V e^{i\vec{k}\vec{r}}E(\vec{r})d\vec{r}.$$

The superscript e in M^e refers to the process taking place in the presence of an electric field.
For a homogeneous field of intensity E we have [11]

$$F_e(\vec{k}) = 8E\sin(\frac{1}{2}ak_x)\sin(\frac{1}{2}bk_y)\sin(\frac{1}{2}ck_z)(k_xk_yk_z)^{-1}. \tag{4}$$

Substituting (4) into (3) we find finally the differential cross section (DCS) of the conversion of the axions in the electric field of a flat condenser of size $a \times b \times c$

$$\frac{d\sigma^e(\gamma\to a)}{d\Omega} = \frac{g_{a\gamma}^2E^2}{2(2\pi)^2}\left[\frac{\sin(\frac{1}{2}ak_x)\sin(\frac{1}{2}bk_y)\sin(\frac{1}{2}ck_z)}{k_xk_yk_z}\right]^2(q_y^2+q_z^2). \tag{5}$$

From (5) we see that if the photon moves in the direction of the electric field i.e., $q^\mu = (q, q, 0, 0)$ then DCS vanishes. If the momentum of photon is parallel to the y axis, i.e., q^μ =(q, 0, q, 0) then Eq. (5) becomes:

$$\begin{aligned}\frac{d\sigma^e(\gamma \to a)}{d\Omega"} &= \frac{32 g_{a\gamma}^2 E^2 q^2}{(2\pi)^2}\left[\sin\left(\frac{ap\sin\theta\sin\varphi"}{2}\right)\sin\left(\frac{b}{2}(q - p\cos\theta)\right)\right.\\ &\times \left.\sin\left(\frac{cp\sin\theta\cos\varphi"}{2}\right)\right]^2 (p^2\sin^2\theta\sin\varphi"\cos\varphi"(q-p\cos\theta))^{-2}. \quad (6)\end{aligned}$$

where $\varphi"$ is the angle between the z axis and the projection of $\vec{p}$ on the xz plane [12]. From (6) we have

$$\frac{d\sigma^e(\gamma \to a)}{d\Omega"} = \frac{2 g_{a\gamma}^2 E^2 a^2 c^2}{(2\pi)^2 q^2\left(1 - \sqrt{1 - \frac{m_a^2}{q^2}}\right)^2}\sin^2\left[\frac{qb}{2}\left(1 - \sqrt{1 - \frac{m_a^2}{q^2}}\right)\right] \quad (7)$$

for $\theta \approx 0$ and

$$\frac{d\sigma^e(\gamma \to a)}{d\Omega"} = \frac{8 g_{a\gamma}^2 a^2 E^2}{(2\pi)^2(q^2 - m_a^2)}\sin^2\left(\frac{bq}{2}\right)\sin^2\left(\frac{cq}{2}\sqrt{1 - \frac{m_a^2}{q^2}}\right) \quad (8)$$

for $\theta = \frac{\pi}{2}, \varphi" = 0$.

In the limit $m_a^2 \to 0$, Eqs. (7) and (8) become, respectively,

$$\frac{d\sigma^e(\gamma \to a)}{d\Omega"} = \frac{g_{a\gamma}^2 q^2 V^2 E^2}{2(2\pi)^2} + O(m_a^4) \quad (9)$$

and

$$\frac{d\sigma^e(\gamma \to a)}{d\Omega"} = \frac{8 g_{a\gamma}^2 a^2 E^2}{(2\pi)^2 q^2}\sin^2\left(\frac{bq}{2}\right)\sin^2\left(\frac{cq}{2}\right) + O(m_a^4). \quad (10)$$

From (9) we see that DCS in the direction of the axion motion depends quadratically on the intensity E, the *volume* V of condenser, and *the photon momentum* q.

For $V = 1m \times 1m \times 1m$, the intensity of the electric field $E = \frac{100kV}{m}$, the photon length $\lambda = 10^{-5}$ cm, and $m_a \simeq 10^{-5} eV$ [9] then in the DFSZ model the cross section given by (9) is $\frac{d\sigma(\gamma\to a)}{d\Omega} \simeq 8 \times 10^{-22} cm^2$, while by (10) $\frac{d\sigma(\gamma\to a)}{d\Omega} \simeq 8 \times 10^{-51} cm^2$. We see that the axion is mainly created in the direction of photon motion. This coincides with the one dimensional solution which is basics for the experimental setups in Ref. [6]. To obtain the results in the KSVZ model we only need to note that $g_\gamma^2(KSVZ) \simeq 7.26 \times g_\gamma^2(DFSZ)$.

For the case in which $q^2 \to m_a^2$, Eqs. (7) and (8) become

$$\frac{d\sigma^e(\gamma \to a)}{d\Omega} = \frac{2 g_{a\gamma}^2 a^2 c^2 E^2}{(2\pi)^2}\sin^2\left(\frac{bq}{2}\right). \quad (11)$$

For $a = c = 1m$, the intensity of the electric field $E = \frac{100kV}{m}$, and $m_a = 1eV$ [9] then the cross section is given by (11): $\frac{d\sigma(\gamma\to a)}{d\Omega} \simeq 8.1 \times 10^{-26} cm^2$

Conversion in the presence of a magnetic field.– Now we consider the conversion in a homogeneous magnetic field of the solenoid with a radius R and a length h, and without loss of generality suppose that direction of the magnetic field is parallel to the z axis, i.e., $F^{12} = -F^{21} = B$. After some manipulations we get

$$\frac{d\sigma^m(\gamma \to a)}{d\Omega} = \frac{g_{a\gamma}^2 F_m^2(\vec{q} - \vec{p})}{2(2\pi)^2} q^2 \left(1 - \frac{q_z^2}{q^2}\right) \tag{12}$$

where F_m is a form factor for the magnetic region [5, 11]:

$$F_m(\vec{k}) = \frac{4\pi BR}{k_z\sqrt{k_x^2 + k_y^2}} J_1(R\sqrt{k_x^2 + k_y^2}) \sin\left(\frac{hk_z}{2}\right). \tag{13}$$

where J_1 is the one-order spherical Bessel function (for a homogeneous magnetic field of magnitude B with a size $a \times b \times c$ one has formula (4) with replacement E by B).

From (12) it follows that when the momentum of the photon is parallel to the z axis (the direction of the magnetic field), DCS vanishes. It implies that *if the momentum of the photon is parallel to the EM field then there is no conversion.* If the momentum of the photon is parallel to the x axis, i.e., $q^\mu = (q, q, 0, 0)$ then Eq. (12) gets the final form:

$$\begin{aligned} \frac{d\sigma^m(\gamma \to a)}{d\Omega'} &= 2g_{a\gamma}^2 R^2 B^2 J_1^2 \left(Rq\sqrt{\left(1 - \cos\theta\sqrt{1 - \frac{m_a^2}{q^2}}\right)^2 + \left(1 - \frac{m_a^2}{q^2}\right)\sin^2\theta\cos^2\varphi'} \right) \\ &\times \left[\left(1 - \cos\theta\sqrt{1 - \frac{m_a^2}{q^2}}\right)^2 + \left(1 - \frac{m_a^2}{q^2}\right)\sin^2\theta\cos^2\varphi' \right]^{-1} q^{-2} \\ &\times \sin^2\left(\frac{hq}{2}\sqrt{1 - \frac{m_a^2}{q^2}}\sin\theta\sin\varphi'\right) \left[(1 - \frac{m_a^2}{q^2})\sin^2\theta\sin^2\varphi'^2 \right]^{-1} \end{aligned} \tag{14}$$

where φ' is the angle between the y axis and the projection of $\vec{p}$ on the yz plane [11]. It is easy to see that

$$\frac{d\sigma^m(\gamma \to a)}{d\Omega'} = \frac{1}{2} g_{a\gamma}^2 R^2 h^2 B^2 J_1^2 \left[Rq\left(1 - \sqrt{1 - \frac{m_a^2}{q^2}}\right) \right] \left(1 - \sqrt{1 - \frac{m_a^2}{q^2}}\right)^{-2} \tag{15}$$

for $\theta \approx 0$ and

$$\frac{d\sigma^m(\gamma \to a)}{d\Omega'} = \frac{1}{2} g_{a\gamma}^2 R^2 h^2 B^2 J_1^2 \left(Rq\sqrt{2 - \frac{m_a^2}{q^2}} \right) \left(2 - \frac{m_a^2}{q^2}\right)^{-1} \tag{16}$$

for $\theta = \frac{\pi}{2}, \varphi' = 0$.
For the limit $m_a^2 \ll q^2$ with the notice that

$$\lim_{p \to q} \frac{J_1\left(R(q-p)\right)}{q-p} = \frac{R}{2}$$

then Eqs. (15) and (16) become, respectively,

$$\frac{d\sigma^m(\gamma \to a)}{d\Omega'} = \frac{g_{a\gamma}^2 V^2 B^2 q^2}{2(2\pi)^2} + O(m_a^4), \qquad V \equiv \pi R^2 h \tag{17}$$

and

$$\frac{d\sigma^m(\gamma \to a)}{d\Omega'} = \frac{1}{4} g_{a\gamma}^2 R^2 h^2 B^2 J_1^2\left(\sqrt{2}Rq\right) + O(m_a^4). \tag{18}$$

From (17) we see that DCS in the direction of photon motion depends quadratically on the magnitude B, *the cavity volume* V and *the photon momentum* q.

From (18) it follows that DCS vanishes when $p_n = \frac{\mu_n}{R\sqrt{2}}$ with $n = 0, \pm 1 \pm 2 ...$and has its largest value

$$\frac{d\sigma^m(\gamma \to a)}{d\Omega'} = \frac{1}{4} g_{a\gamma}^2 R^2 h^2 B^2 J_1^2(\mu'_n) \tag{19}$$

for $p_n = \frac{\mu'_n}{R\sqrt{2}}$, where μ_n and μ'_n are the roots of $J_1(\mu_n) = 0$ and $J'_1(\mu'_n) = 0$.

For the magnetude [9] B $= 8$T,$R = h = 1m$, $\lambda = 10^{-5}cm$ and $m_a \simeq 10^{-5}eV$ by (17) we have $\frac{d\sigma(\gamma \to a)}{d\Omega} = 4.7 \times 10^{-11} cm^2$.

For the limit $q^2 \to m_a^2$, Eqs. (15) and (16) become:

$$\frac{d\sigma^m(\gamma \to a)}{d\Omega'} = \frac{1}{2} g_{a\gamma}^2 R^2 h^2 B^2 J_1^2\left(Rq\right). \tag{20}$$

For B $= 8$ T, $m_a = 1eV$ and $R = h = 1m$, we have $\frac{d\sigma_(\gamma \to a)}{d\Omega} = 1.7 \times 10^{-16} cm^2$.

In the case of the magnetic field of size $a \times b \times c$ we get a formula similar to (17) under the same conditions.

It is easy to show that the cross section for the reverse process coincides exactly with above results, so that for conversion photon-axion-photon, cross section is square of the previous evaluation.

Based on the above we describe an experiment: The initial photon of energy q_o from the laser (maybe better from X ray) interacts with a virtual photon from the EM field to produce the axion of energy q_o and momentum $p = (q_o^2 - m_a^2)^{1/2}$. The photon beam is then blocked to eliminate everything except the axions, which penetrate the wall because of their extremely weak interaction with ordinary matter. (Such shielding is straightforward for a low-energy laser beam.) The axion then interacts with another virtual photon in the second EM field to produce a real photon of energy q_o, whose detection is the signal for the production of the axion. For the details of experimental setup the reader can see Refs. [6, 15].

We note again that here EM field is understood by not only magnetic field but also *the electric field of the condenser*. To differ the axion signal from noise the case in which the EM field is switched off has to be measured. From the results we can get limits for f_a as well as on the axion mass. The axion-photon coupling constant in [10] is taken $g = 10^{-8}$ GeV^{-1}, this coupling constant corresponds to the axion mass $m_a \sim 0.1$ eV.

We emphasize that the cross section depends quadratically on the momentum of incoming photons hence high frequencies are preferred despite the technical difficulties discussed in [10].

In conclusion, the axion hypothesis can be tested experimentally. Relatively simple experiments can provide new information about physics at very high energies. If the axion exists, we will have new powerful tools to study the galaxy and the sun.

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References

[1] R. D. Peccei and H. Quinn, Phys. Rev. Lett. **38**, 1440 (1977); Phys. Rev. **D16**, 1792 (1977).

[2] S. Weinberg, Phys. Rev. Lett. **40**, 223 (1977); F. Wilczek, *ibid.* **40**, 279 (1977).

[3] M. Minowa, Y. Inoue, T. Asanuma, and M. Imamura, Phys. Rev. Lett. **71** 4120 (1993); J. E. Kim, Phys. Rep. **150**, 1 (1987); H. Y. Cheng, Phys. Rep. **158**, 1 (1988); R. D. Peccei, in *CP Violation*, edited by C. Jarlskog (Advanced Series on Directions in High Energy Physics, Vol. 3) (World Scientific, Singapore, 1989).

[4] M. S. Turner, Phys. Rep. **197**, 67 (1990); G. G. Raffelt, Phys. Rep. **198**, 1 (1990); E. W. Kolb and M. S. Turner, *The Early Universe*, Addison- Wesley Publ. Company, 1990.

[5] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983); Phys. Rev. **D32**, 2988 (1985); in *CP Violation in Particle Physics and Astrophysics*, edited by Jean Tran Thanh Van, Editions Frontières, 1989.

[6] K. Van Bibber, N. R. Dagdeviren, S. E. Koonin, A. K. Kerman, and H. N. Nelson, Phys. Rev. Lett. **59**, 759 (1987).

[7] S. DePanfilis, A. C. Melissinos, B. E. Moskowitz, J. T. Rogers, Semertzidis, W. U. Wuensch, H. J. Halama, A. G. Prodell, W. B. Fowler, and F. A. Nezrick, Phys. Rev. Lett. **59**, 839 (1987).

[8] F. Hoogeveen and T. Ziegenhagen, Nucl. Phys. **B358**, 3 (1991).

[9] C. Hagman, P. Sikivie, N. S. Sullivan, and D. B. Tanner, Phys. Rev. **D42**, 1297 (1990); P. Sikivie, D. B. Tanner, and Yun Wang, Phys. Rev. **D50**, 4744 (1994).

[10] F. Hoogeveen, Phys. Lett. **B288**, 195 (1992).

[11] H. N. Long, D. V. Soa, and Tuan A. Tran, Mod. Phys. Lett. **A9**, 3619 (1994).

[12] H. N. Long, D. V. Soa, and Tuan A. Tran, Phys. Lett. **A186**, 382 (1994).

[13] M. Dine, W. Fischler, and M. Srednicki, Phys. Lett. **B104**, 199 (1981); A. P. Zhitnitskii, Yad. Fiz. **31**, 497 (1980) [Sov. J. Nucl. Phys. **31**, 260 (1980)].

[14] J. Kim, Phys. Rev. Lett. **40**, 223 (1977); M.A. Shifman, A. I. Vainshtein, and V. I. Zakharov, Nucl. Phys. **B166**, 493 (1980).

[15] A. A. Anselm, Yad. Fiz. **42**, 1480 (1985) (Sov. J. Nucl. Phys., **42**, 936 (1985)).